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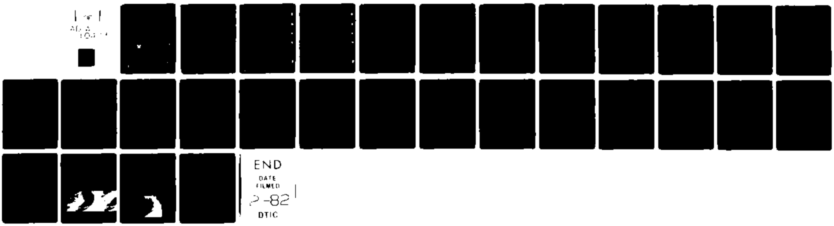

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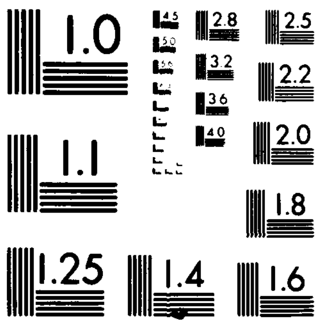

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Princeton University

Department of
Mechanical and
Aerospace Engineering

SHOCK WAVE/TURBULENT BOUNDARY LAYER
INTERACTIONS IN TWO AND THREE DIMENSIONS

Gary S. Settles

Final Scientific Report for

CONTRACT F49620-80-C-0092
1 August 1980 through 31 July 1981

MAE REPORT 1546
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TURBULENCE	FLOW MEASUREMENT TECHNIQUES	HOT-WIRE [illegible]ETRY
BOUNDARY LAYERS	TWO-DIMENSIONAL FLOWS	SCALING LAWS
SHOCK WAVES	THREE-DIMENSIONAL FLOWS	
COMPRESSION CORNERS	FLOW REATTACHMENT	

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

During the contract period of August 1980 through July 1981 the Gas Dynamics Laboratory of Princeton University has carried out basic experimental research in two and three-dimensional shock wave/boundary layer interactions and associated turbulence measurements. The primary emphasis ~~of this work~~ has been in exploring the important but little-known range of three-dimensional interactions at high speeds. Building on previous work ~~under AFOSR sponsorship~~ a series of parametric experiments and a detailed analysis have led to the synthesis of scaling laws for Reynolds number effects on these interactions.

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PREPARED FOR

AIR FORCE OFFICE OF SCIENTIFIC RESEARCH
BOLLING AIR FORCE BASE,
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PREPARED BY

GAS DYNAMICS LABORATORY
DEPARTMENT OF MECHANICAL AND AEROSPACE ENGINEERING
PRINCETON UNIVERSITY, PRINCETON, NJ

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1. INTRODUCTION

This Final Scientific Report summarizes the research efforts carried out by the Gas Dynamics Laboratory of the Mechanical and Aerospace Engineering Department, Princeton University, under Contract F49620-80-C-0092 of the U. S. Air Force Office of Scientific Research, during the 1980-81 contract period. This research has dealt with the problems of compressible flow and shock wave/boundary layer interactions in two and three dimensions and at flight-scale Reynolds numbers. The aim of this research is to provide some fundamental physical understanding of these complex flows by way of detailed measurements and analyses.

Several individual studies have proceeded during this contract. The primary emphasis of the research has been in exploring the important but little-known range of three-dimensional (3-D) interactions at high speeds. Building on previous work under AFOSR sponsorship, a series of parametric experiments and a detailed analysis have led to the synthesis of scaling laws for Reynolds number effects on these interactions.

Further experiments continued the adaptation and use of hot-wire anemometry in high-Reynolds number supersonic flows. Hot-wire surveys were made in the previously-explored flowfield of a reattaching free shear layer, and in the interaction generated by a two-dimensional (2-D) compression corner of 8° deflection angle at Mach 3.

Other research activities under the subject contract have included the development of new flow visualization methods for high-speed 3-D flows, the completion and initial calibration of a computerized 3-D yaw probe, and the preparation of previous AFOSR-sponsored experimental results for inclusion in the Data Library of the 1980-81 AFOSR-HTTM-Stanford Conference on Complex Turbulent Flows. Since detailed reports of this research program have appeared or will appear in technical journals and publications (see Bibliography and References), the present treatment is kept appropriately brief.

2. SHOCK/BOUNDARY LAYER INTERACTION SCALING IN TWO AND THREE DIMENSIONS

Shock wave interactions with compressible turbulent boundary layers have been studied many times by past investigators. Most of these studies have concerned the two-dimensional or semi-infinite case because the past investigators felt that the problem was already sufficiently complex without the added difficulty of a third dimension. They proceeded to attempt to characterize these 2-D interactions through experimental measurements and some approximate calculations.

The earliest investigators (e.g., Refs. 1 and 2) learned that the streamwise length scales of these interactions depended upon Mach number, Reynolds number, overall pressure rise, incoming boundary layer thickness, and (sometimes) experimental geometry. Through the years, as a body of experimental evidence was built up, empirical correlations and approximate analyses have evolved into what we now know as the scaling laws of 2-D shock/boundary layer interactions, which describe — with mixed accuracy — the effects of the above parameters on interaction length scales (Ref. 3).

However, even with the simplifying assumption of 2-D flow, some of these scaling laws have not been developed sufficiently to provide a general picture of the interaction scaling. For example, it often has been assumed (e.g., Refs. 2 and 4) that the length scale of a 2-D interaction is proportional to the incoming turbulent boundary layer thickness, δ_0 , if all other parameters are held constant. Limited experimental data supported this view for many years. Only recently have more detailed studies (Refs. 3, 5 and 6) shown that this is an oversimplification, and that the Reynolds number is also an important part of the interaction scale.

Figure 1 (from Ref. 6) illustrates the Reynolds number and boundary layer thickness scaling of upstream influence ahead of 2-D Mach 3 compression corners as we now understand it. Stated simply, if δ_0 is taken as the interaction scale, then a Re_{δ_0} "residual" effect remains to be taken into account. This has been done in Figure 1, where good agreement among the

three leading experiments in the field is shown in terms of an empirical δ_0 and Re_{δ_0} scaling function.

Still, the scaling of 2-D interactions is not yet perfectly understood. The physical mechanism of upstream influence, for example, has been the subject of a long-term effort by many distinguished researchers, and is still not clear. Recent developments in the so-called "triple-deck" theory (Ref. 7) may point the way to an eventual understanding of this mechanism.

While some questions remain about the generality and physical basis of the 2-D interaction scaling laws, there is nevertheless a reasonable scaling framework with which to proceed. The situation for 3-D interactions, unfortunately, is not nearly so clear. Far fewer 3-D experiments have been done, and each one has seemed to stand by itself with little obvious connection to the others. While the individual 3-D experiments have shown some radical departures from the known 2-D behavior, it has not been possible to judge from them how large a particular 3-D interaction scale should be, or how it might vary with δ_0, Re, M_∞, shock strength, etc. Basic knowledge has been lacking, both in terms of a sufficient range of experimental measurements and a framework within which to relate them.

This problem has been studied in recent years by Settles, Dolling, Oskam, Bogdonoff, and other investigators at the Princeton University Gas Dynamics Laboratory (Refs. 6, 8-11). These efforts have been concentrated on a particular class of simple 3-D geometries which produce representative (though not necessarily simple) 3-D interactions. This class of geometries, illustrated in Figure 2, includes those which we call the "sharp fin," "swept fin," "blunt fin," and "swept compression corner."

During the past year a concentrated effort was made to obtain data on the upstream influence scales of the swept compression corner and sharp fin interactions. These data were deliberately taken over wide ranges of incoming turbulent boundary layer thickness and unit Reynolds number. The resulting data sets were analyzed in hopes of finding some common principle to relate the scaling of both interactions.

After a considerable effort (in which it was first necessary to re-examine the 2-D Re and δ_0 scaling), this goal was accomplished. Its detailed development is given in Refs. 6 and 11. Briefly, the streamwise scaling of upstream influence is the same as in 2-D flow, but an analogous spanwise scaling function is required for 3-D interactions, which, unlike 2-D cases, develop and change in both streamwise and spanwise directions.

The general scaling law, applicable to 2-D and 3-D shock/boundary layer interactions, is given by:

$$\frac{L_m \, Re^{-a}}{\delta_\ell^{\,a+1}} = \mathrm{fn}\left(\frac{z \, Re^{-a}}{\delta_\ell^{\,a+1}}, \alpha, \lambda, M_\infty, \ldots\right), \tag{1}$$

where L_m = upstream influence distance

Re = freestream Reynolds number, = freestream velocity/kinematic viscosity

δ_ℓ = local incoming equilibrium turbulent boundary layer thickness

a = a constant ($-1/3$ for $M_\infty \approx 3$ and high Reynolds numbers)

α,λ = two angles which specify the 3-D shock strength and sweepback

z = spanwise coordinate, and

M_∞ = freestream Mach number

A complete discussion and physical interpretation of this scaling law is given in Ref. 6. Its empirical justification is shown in Figs. 3 and 4, where both sharp fin and swept compression corner interactions are scaled, in terms of Re and δ effects, by the scaling law as given above.

Figures 3 and 4 represent physical pictures of the interaction development in both the streamwise and spanwise directions, in terms non-dimensional in Re and δ. The shape of the "footprint" of the interaction is fixed by a given choice of α, λ, and M_∞, but the dimensional scale can be compressed or expanded by changes in Re and δ. For a test model or a control surface of fixed dimensions, one can "see farther out" along the non-dimensional spanwi · develc .nt of the interaction if Re is increased

or δ is decreased, or both. This has important implications for the test conditions required to fully explore 3-D interactions in wind tunnels of limited size.

No scaling functions are presented here for the effects of α, λ, and M_∞. These are elements of the 3-D interaction behavior which are not yet understood, and which are the subject of ongoing research.

3. TURBULENT MEASUREMENTS VIA HOT-WIRE ANEMOMETER

Hot-wire anemometry techniques for high-speed high-Reynolds number flows have been developed at the Gas Dynamics Laboratory under previous AFOSR sponsorship, and were first applied to the study of a reattaching free shear layer (Ref. 12). These preliminary measurements were repeated during the current contract year.

There were several reasons for repeating the measurements. These included establishing the validity of the measurement technique, exploring the causes of possible errors in the technique which might lead to improvements therein, and establishing a more firm data base on the fluctuating properties of high-speed reattachment. Specifically, the repeatability of the hot-wire measurements was checked in terms of the effects of using different probes and varying both the physical spacing of the measurement points and the number of high-frequency records taken at each point.

Figure 5 illustrates the excellent repeatability that can be obtained when several surveys are made with the same hot-wire probe. It also demonstrates that reasonable changes in vertical step size have a negligible effect on the final result, and that 25,600 readings (25 records at 1024 readings each) are sufficient to obtain convergence in terms of fluctuation intensity.

However, some deterioration in repeatability (not illustrated here) was observed when different hot-wire probes were used. Modifications in the wire calibration routine are being implemented to alleviate this problem.

In a separate hot-wire investigation carried out during the contract period, detailed surveys were made in the flowfield generated by a 2-D, 8° compression corner at $M \sim 3$. The mean-flow measurements of this flow, previously carried out by Settles, et.al. (Ref. 13), reveal a weak shock/boundary layer interaction with no flow separation. The only other turbulence measurements available for compression corners seem to be those by Ardonceau, et.al. (Ref. 14).

The configuration investigated is sketched in Figure 6. The incoming two-dimensional turbulent boundary layer develops without pressure gradient and has an overall thickness, δ_o, of approximately 26mm. The freestream conditions are: Mach number = 2.85 and unit Reynolds number = 7.3×10^7/m, and the wall conditions are near adiabatic. The 8° compression corner model was installed on the tunnel floor.

The mean wall static pressure distribution for this model is shown in Figure 7. In this and the following figures, x = 0.0 corresponds to the corner position, and the negative and the positive x values denote upstream and downstream distances from the corner, respectively.

The main data obtained in this study are represented in Figures 8-10. The r.m.s. value of the mass-flow fluctuation $\langle\rho u'\rangle$, was normalized by the local mean mass flow, $\overline{\rho u}_L$, and the mean freestream mass flow upstream of the shock wave, $\overline{\rho u}_E$. The location of the shock wave, measured from a schlieren photograph, is indicated by the arrows in the figures. It can be seen from Figures 8(a) and (b) that the level of the mass flow fluctuation increases significantly after the shock wave. The maximum value of $\langle\rho u'\rangle/\overline{\rho u}_E$ is plotted in Figure 9 as a function of streamwise distance. This clearly shows a rapid rise in the maximum fluctuation level after the corner. This is followed by a gradual rise up to the most downstream station, approximately 6 δ_o downstream of the corner. It should be noted that the wake-strength parameter, π, (obtained from the mean velocity profiles) begins to decrease almost immediately after the corner (Ref. 13), indicating that, in contrast to the turbulence behavior, the mean flow quantities do appear to relax toward their equilibrium values.

The profiles of $\langle\rho u'\rangle/\overline{\rho u}_E$ are plotted against y/δ in Figure 10. This figure clearly shows how the fluctuation level is amplified through the severe adverse pressure gradient. The region where the amplification occurs is confined to the portion of the boundary layer downstream of the shock wave, and the rest of the boundary layer remains relatively undisturbed.

These results will be discussed in more detail in an upcoming technical paper (Ref. 15).

4. TECHNIQUE, INSTRUMENTATION, AND FACILITY DEVELOPMENT

Techniques and instrumentation are always important considerations in experiments aimed at such a complex phenomenon as a shock/boundary layer interaction. The Gas Dynamics Laboratory maintains a constant effort to develop new techniques and instrumentation while at the same time investigating fluid flows. During the contract period, progress has been made in three such development efforts: 3-D flow visualization, yaw measurements in 3-D flows via "cobra" probe, and the extension of our testing capability to another Mach number.

Flow visualization in high-speed, 3-D, turbulent boundary layer flows is a triply complicated problem. Of the massive body of literature available on flow visualization (see, for example, Ref. 16), very little is found to apply to such conditions. Yet it is well known that such visualization is necessary in order to gain a physical understanding of the flow, and to guide more quantitative measurements using other instruments.

Preliminary tests were begun in order to develop new techniques or modify previous techniques of flow visualization for high-speed, 3-D turbulent flows. The results of a modest effort were quite encouraging, in that five relatively simple methods were found to be useful: kerosene-lampblack surface streak traces, localized vapor visualization, conical shadowgraphy, stereoscopic schlieren photography, and incandescent particle tracers.

The most useful of these techniques is the localized vapor visualization, the possibility of which does not appear to have been identified in the previous literature. This new technique was applied to 3-D flows generated by swept compression corners, as sketched in Figure 11. Briefly, a volatile fluid such as acetone is introduced into the flow through pressure taps or other orifices. The fluid vaporizes and generates a locally dense fog which can be illuminated stroboscopically and photographed stereoscopically to record 3-D information. A typical pair of stereo photos in Figure 12 demonstrates that the turbulent boundary layer detaches from the surface ahead of a swept corner defined by $\alpha = 24°$ and $\lambda = 40°$ at Mach 3.

Another quite useful flow visualization technique is conical shadowgraphy, which is done by generating a conical light beam at the apex of an approximately conical 3-D shock/boundary layer interaction. A sketch of the experimental arrangement and a typical conical shadowgram from the swept corner experiment series are reproduced here in Figure 13.

A complete description of the five flow visualization techniques developed in this preliminary study is given in Ref. 17. Work along these lines is still continuing at the Gas Dynamics Laboratory.

Another technique which progressed during the contract period was that of the computer-driven yaw probe for surveying 3-D flowfields. This instrument, under development in the Gas Dynamics Laboratory for several years, is designed to null itself automatically to the local flow direction by means of a differential pressure signal, a controlling computer program, and a stepping-motor driver (see schematic, Fig. 14).

During the contract period, this new instrument was tested in a 3-D shock/boundary layer interaction to determine whether or not it functioned correctly. The results were excellent, both in terms of the proper convergence of the nulling process and the speed and accuracy of computerized control, which are well beyond what can be done by manual nulling. Pending a few remaining tests, the automated yaw probe is ready for use in investigating 3-D interactions.

Finally, efforts were under way during the contract period to extend the testing capability of the Princeton High Reynolds Number Blowdown Wind Tunnel. Our previous studies of 3-D shock/boundary layer interactions have pointed toward the need for experiments at more than one Mach number in order to evaluate properly the scaling laws governing such interactions (see Section 2).

It was decided to design a new nozzle for the blowdown facility at a lower Mach number than $M \sim 3$, where most current tests have been performed. Analyses of probable changes in wave angles and pressure distributions led

us to choose $M \sim 2$ for this purpose. A method-of-characteristics nozzle design computer program was run for our conditions by Dr. R. L. P. Voisinet of The Naval Surface Weapons Center, White Oak, MD. The detailed design and construction of the new nozzle will be carried out during the 1981-82 contract year.

5. OTHER RESEARCH ACTIVITIES

Participation in the 1980-81 AFOSR-HTTM-Stanford Conference on Complex Turbulent Flows was included in our research activities during the contract period. This participation involved preparing data sets for inclusion in the Data Library generated by the Conference (see Report Bibliography), and attending and participating in the first of two meetings of the Conference, held at Stanford University during September 1980.

Data from two previous AFOSR-sponsored experimental programs carried out at the Gas Dynamics Laboratory were included in the Stanford Data Library. These programs involved 2-D compression corner interactions (Ref. 13) and the reattachment of a turbulent free shear layer at high speeds (Ref. 12). These data serve as test cases for the testing and guidance of computational fluid dynamics methods. A great deal of care was taken, both in the original experiments and in their documentation, to provide competent and consistent data sets for this purpose. These fully-documented experiments and some fifty others by different investigators make up the complete Data Library of the Stanford Conference, which is available on computer tape from COSMIC, 112 Barrow Hall, Univ. of Georgia, Athens, GA 30602.

REPORT BIBLIOGRAPHY

1) Settles, G. S., Gilbert, R. B. and Bogdonoff, S. M., "Data Compilation for Shock Wave/Turbulent Boundary Layer Interaction Experiments on Two-Dimensional Compression Corners," MAE Report #1489. Data sets for inclusion in the Data Library generated by the 1980-81 AFOSR-HTTM-Stanford Conference on Complex Turbulent Flows, Stanford Univ., September 1980.

2) Horstman, C. C., Settles, G. S., Bogdonoff, S. M. and Williams, D. R., "A Reattaching Free Shear Layer in Compressible Turbulent Flow - A Comparison of Numerical and Experimental Results," AIAA 19th Aerospace Sciences Meetings, St. Louis, Missouri, AIAA Paper #81-0333, January 1981.

3) Settles, G. S., Perkins, J. J. and Bogdonoff, S. M., "Upstream Influence Scaling of 2D & 3D Shock/Turbulent Boundary Layer Interactions at Compression Corners," AIAA 19th Aerospace Sciences Meeting, St. Louis, Missouri, AIAA Paper #81-0334, January 1981. Also submitted for publication in the AIAA Journal.

4) Dolling, D. S. and Bogdonoff, S. M., "Upstream Influence Scaling of Sharp Fin-Induced Shock Wave Turbulent Boundary Layer Interactions," AIAA 19th Aerospace Sciences Meeting, St. Louis, Missouri, AIAA Paper #81-0336, January 1981.

5) Baca, K. B., "An Experimental Study of the Reattachment of a Free Shear Layer in Compressible Turbulent Flow," MSE Thesis, Dept. of Mechanical & Aerospace Engineering, Princeton University, submitted December 1981.

6) Settles, G. S. and Teng, H.-Y., "Flow Visualization of Separated 3D Shock Wave/Turbulent Boundary Layer Interactions," AIAA 20th Aerospace Sciences Meeting, Orlando, Florida, AIAA Paper #82-0229, January 1982.

REFERENCES

1. Bogdonoff, S. M. and Kepler, C. E., "Separation of a Supersonic Turbulent Boundary Layer," J. Aero. Sci., 22, 1955, pp. 414-424.

2. Drougge, G., "Experimental Investigation of the Influence of Strong Adverse Pressure Gradients on Turbulent Boundary Layers at Supersonic Speeds," 6th Intn'l. Congress on Theoretical and Applied Mechanics, Istanbul, 1952.

3. Green, J. E., "Interactions Between Shock Waves and Boundary Layers," Progress in Aerospace Sciences, Vol. 11, 1970, pp. 234-340.

4. Erdos, J. and Pallone, A., "Shock-Boundary Layer Interaction and Flow Separation," AVCO RAD-TR-61-23, 1961.

5. Settles, G. S., Bogdonoff, S. M. and Vas, I. E., "Incipient Separation of a Supersonic Turbulent Boundary Layer at High Reynolds Numbers," AIAA Journal, Vol. 14, Jan. 1976, pp. 50-56.

6. Settles, G. S., Perkins, J. J. and Bogdonoff, S. M., "Upstream Influence Scaling of 2D and 3D Shock/Turbulent Boundary Layer Interactions at Compression Corners," AIAA Paper 81-0334, January 1981.

7. Inger, G. R., "Upstream Influence and Skin Friction in Non-Separating Shock-Turbulent Boundary Layer Interactions," AIAA Paper 80-1411, July 1980.

8. Oskam, B., Vas, I. E. and Bogdonoff, S. M., "Mach 3 Oblique Shock Wave/ Turbulent Boundary Layer Interactions in Three Dimensions," AIAA Paper 76-336, July 1976.

9. Dolling, D. S., Cosad, C. D. and Bogdonoff, S. M., "An Examination of Blunt-Fin Induced Shock Wave Turbulent Boundary Layer Interactions," AIAA Paper 79-0068, January 1979.

10. Settles, G. S., Perkins, J. J. and Bogdonoff, S. M., "Investigation of Three-Dimensional Shock/Boundary-Layer Interactions at Swept Compression Corners," AIAA Journal, Vol. 18, July 1980, pp. 779-785.

11. Dolling, D. S. and Bogdonoff, S. M., "Upstream Influence Scaling of Sharp Fin-Induced Shock Wave Turbulent Boundary Layer Interactions," AIAA Paper 81-0336, January 1981.

12. Settles, G. S., Baca, B. K., Williams, D. R. and Bogdonoff, S. M., "A Study of Reattachment of a Free Shear Layer in Compressible Turbulent Flow," AIAA Paper 80-1408, July 1980.

13. Settles, G. S., Fitzpatrick, T. J. and Bogdonoff, S. M., "Detailed Study of Attached and Separated Compression Corner Flowfields in High Reynolds Number Supersonic Flow," AIAA Journal, Vol. 17, No. 6, pp. 579-585, June 1979.

14. Ardonceau, P., Lee, D. H., Alziary de Roquefort, T. and Goethals, R., "Turbulence Behavior in Shock Wave/Boundary Layer Interaction," NATO AGARD CP-271 'Turbulent Boundary Layers - Experiments, Theory and Modelling,' 1979.

15. Hayakawa, K., Smits, A. J. and Bogdonoff, S. M., "Hot-Wire Investigation of an Unseparated Shock-Wave/Turbulent Boundary Layer Interaction," submitted to AIAA/ASME Joint Fluids, Plasma, Thermophysics, and Heat Transfer Conferences, to be held June 7-11, 1982 in St. Louis, Missouri.

16. Merzkirch, H., Flow Visualization, Academic Press, 1974.

17. Settles, G. S. and Teng, H.-Y., "Flow Visualization of Separated 3D Shock Wave/Turbulent Boundary Layer Interactions," AIAA Paper 82-0229, January 1982.

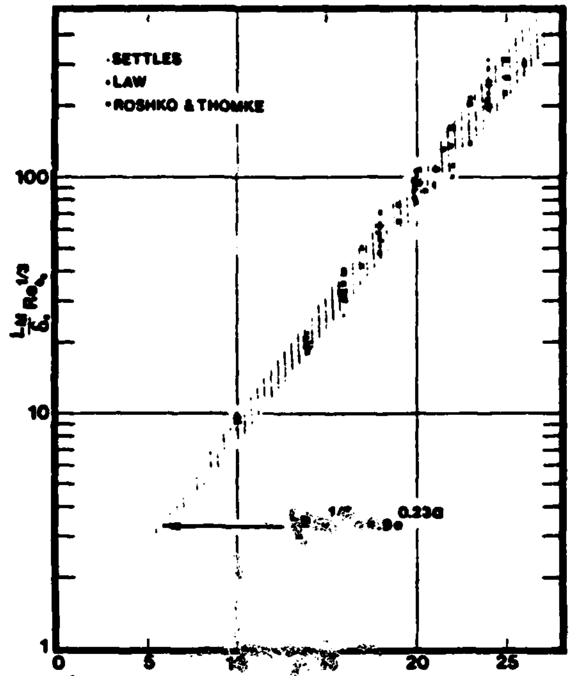


Fig. 1. Compression [illegible] Upstream Influence Correlation, [illegible] $\le Re_{\delta_0} \le 10^7$, $10^\circ \le \alpha \le 26^\circ$.

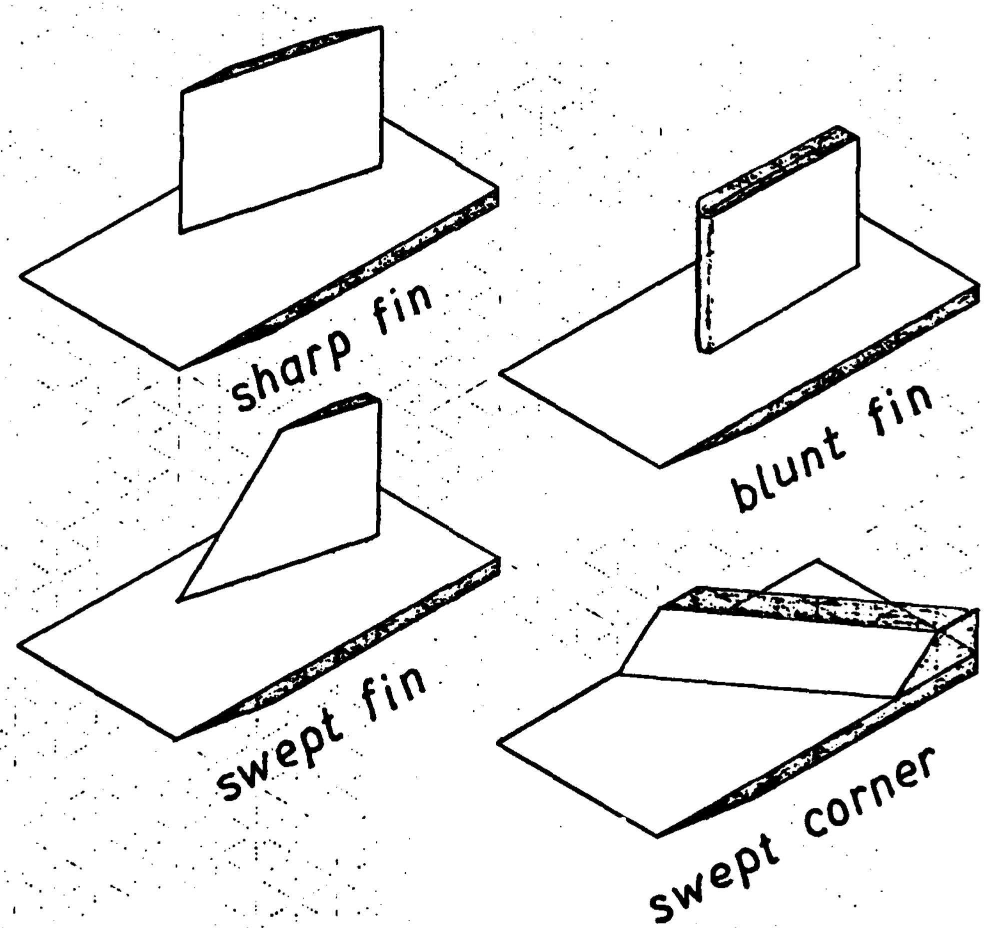


Fig. 2. Test Geometries for a Class of 3D Shock/Turbulent Boundary Layer Interactions.

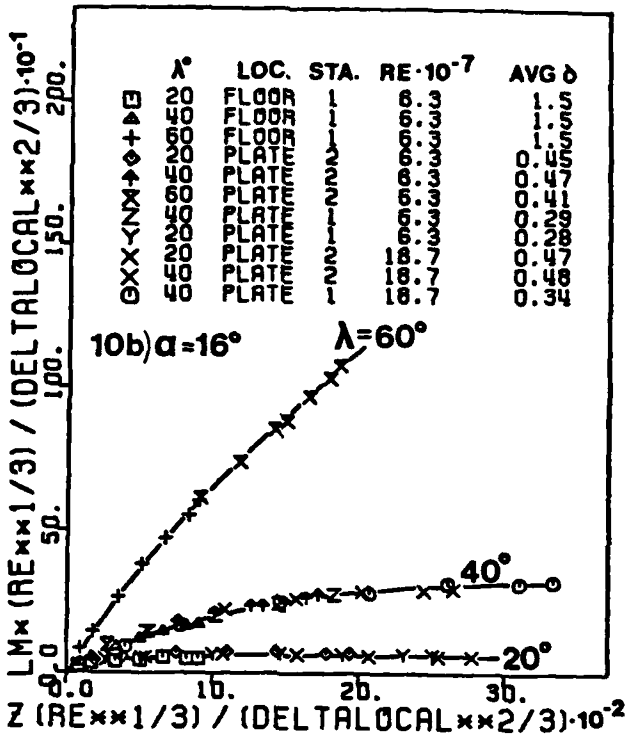


Fig. 3. Example of Streamwise and Spanwise Upstream Influence Scaling for Swept Compression Corner Interactions.

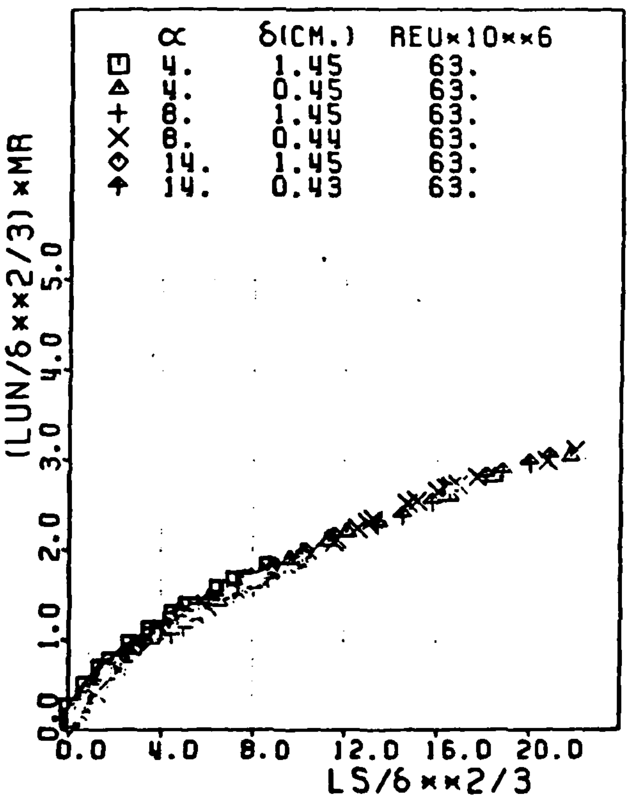


Fig. 4. Example of Streamwise and Spanwise Upstream Influence Scaling for Sharp Fin Interactions.

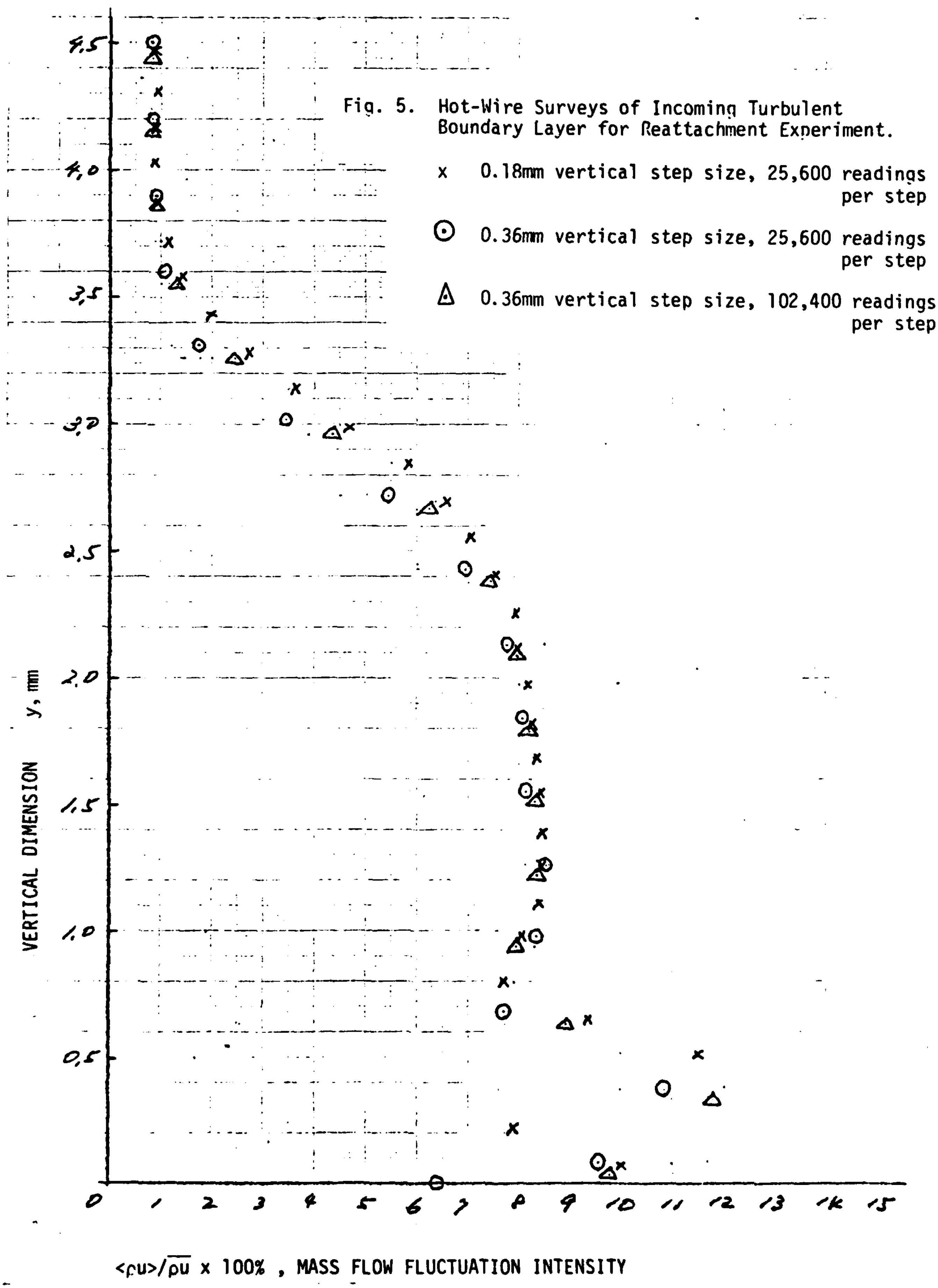


Fig. 5. Hot-Wire Surveys of Incoming Turbulent Boundary Layer for Reattachment Experiment.

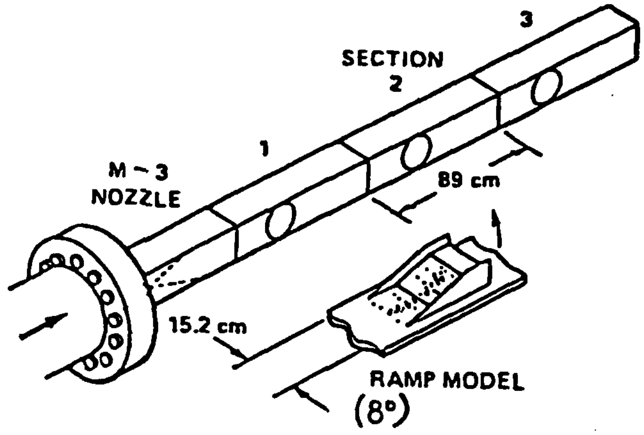


Fig. 6. Sketch of the 20 x 20 cm High Reynolds Number Channel and Test Model Installation.

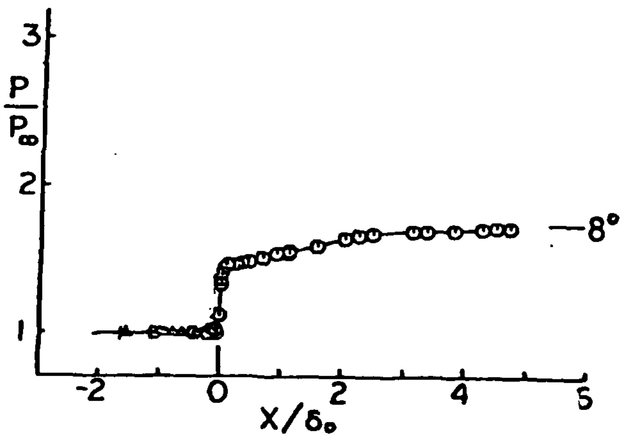


Fig. 7. Surface Pressure Distribution on the 8° Compression Corner Model.

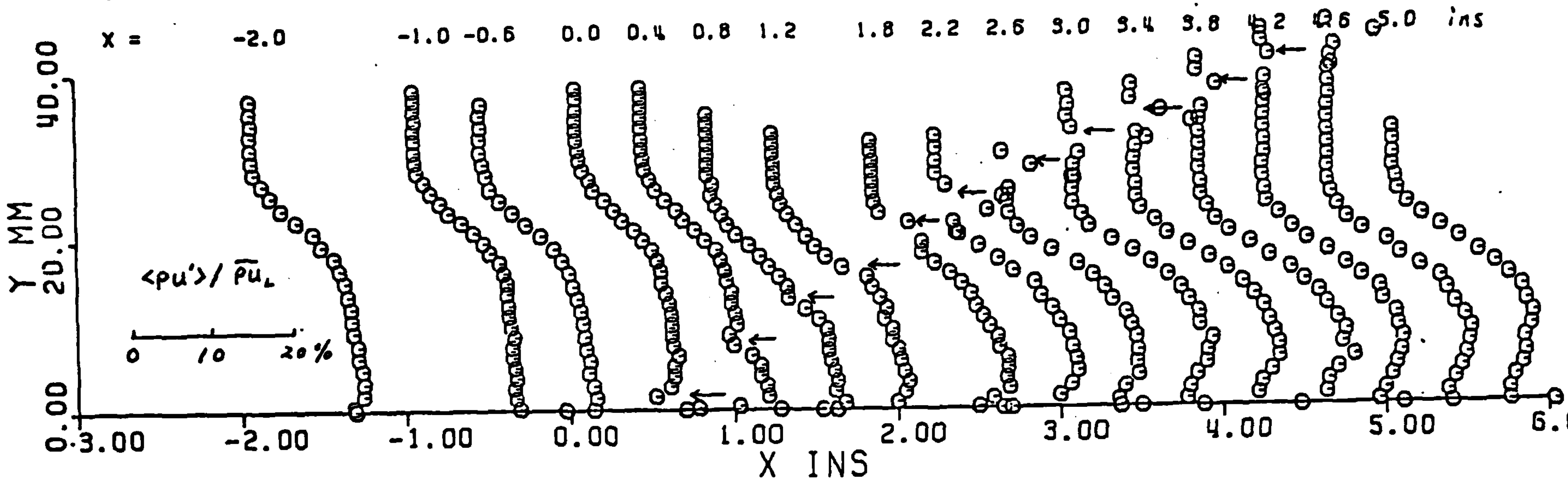


Fig. 8(a). Profiles of $\langle \rho u' \rangle / \overline{\rho u}_L$

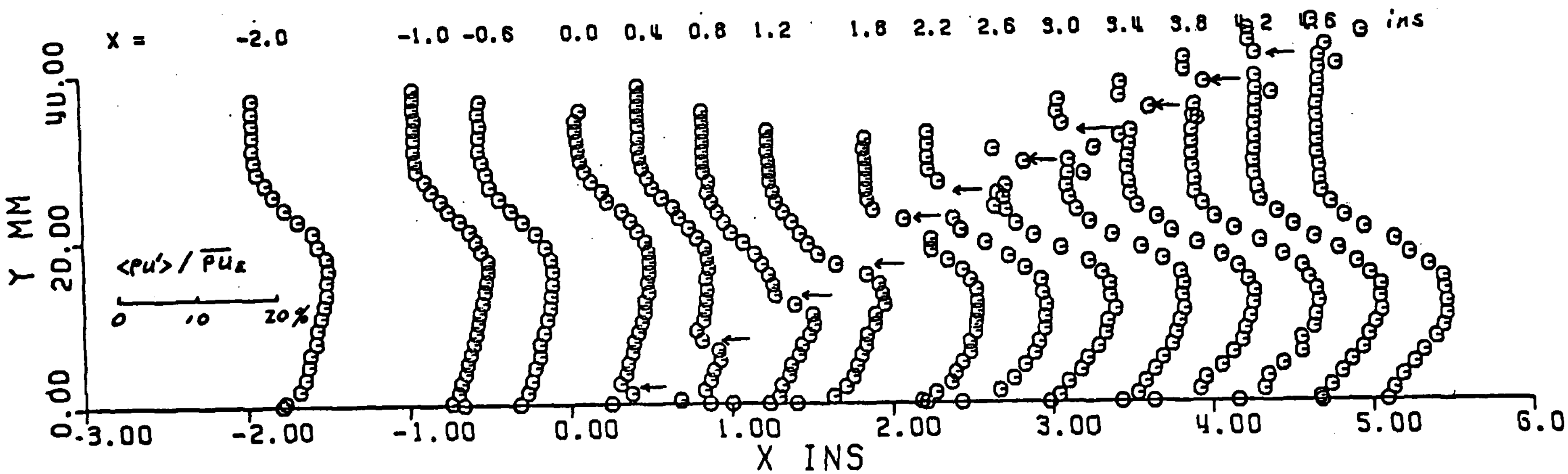


Fig. 8(b). Profiles of $\langle \rho u' \rangle / \overline{\rho u}_E$

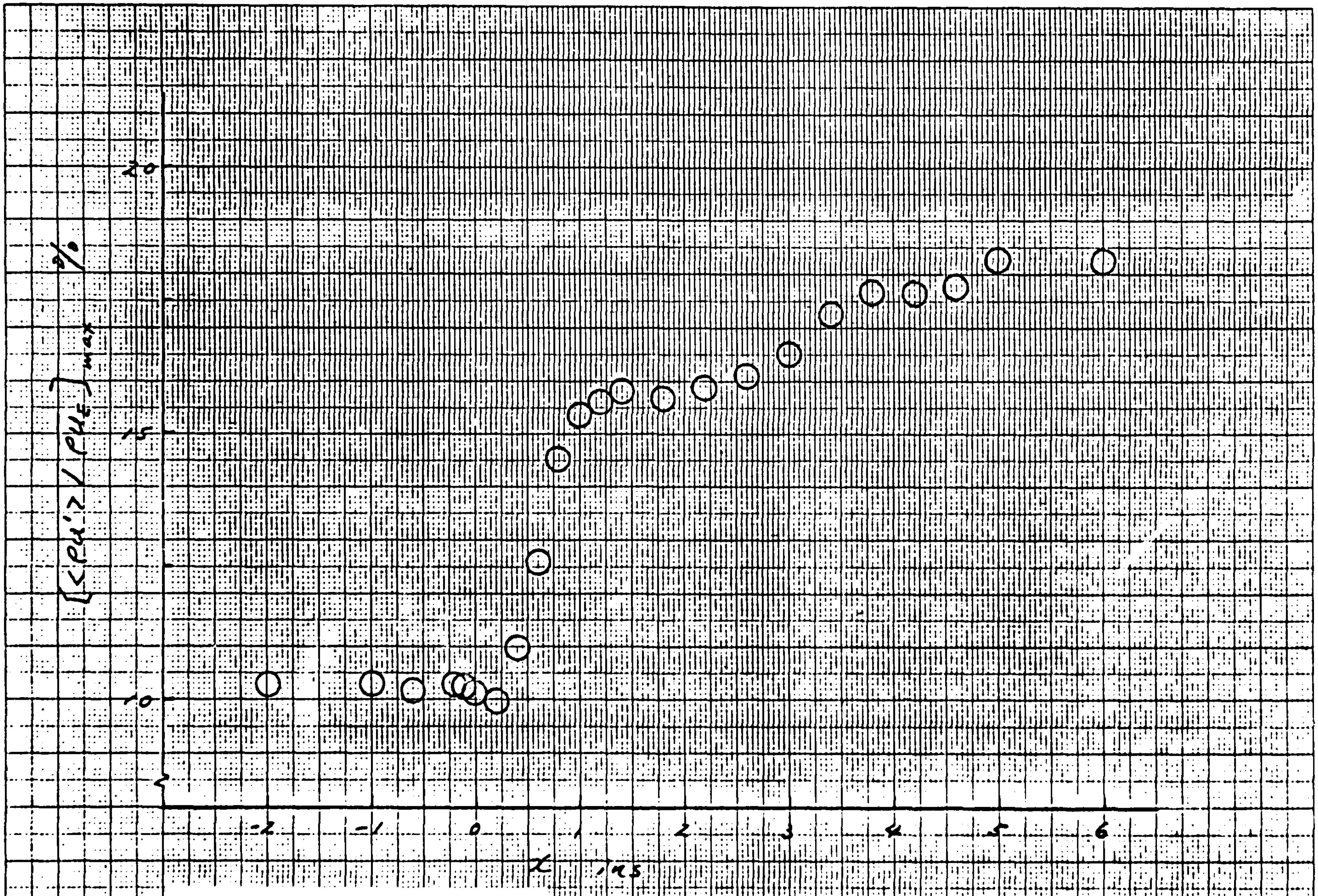


Fig. 9. $[\langle \rho u' \rangle / \overline{\rho u_E}]_{max}$ vs. X

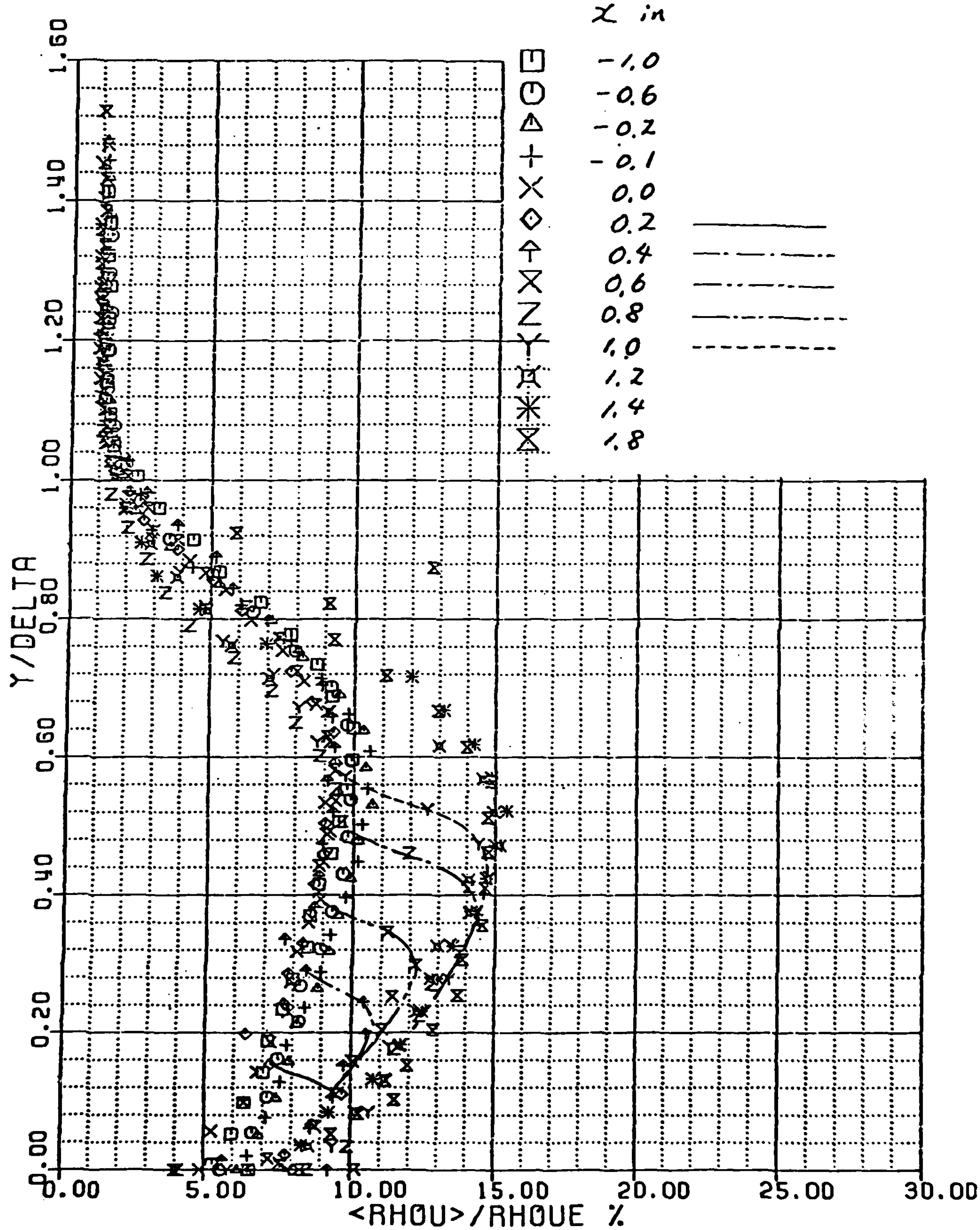


Fig. 10. $\langle \rho u' \rangle / \overline{\rho u_E}$ vs. y/δ

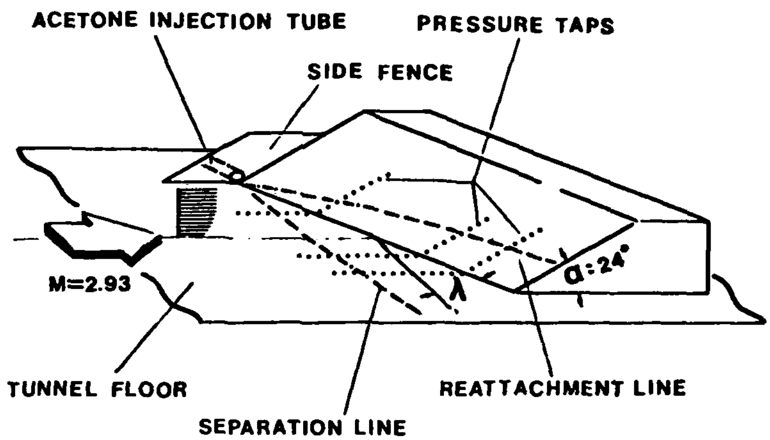
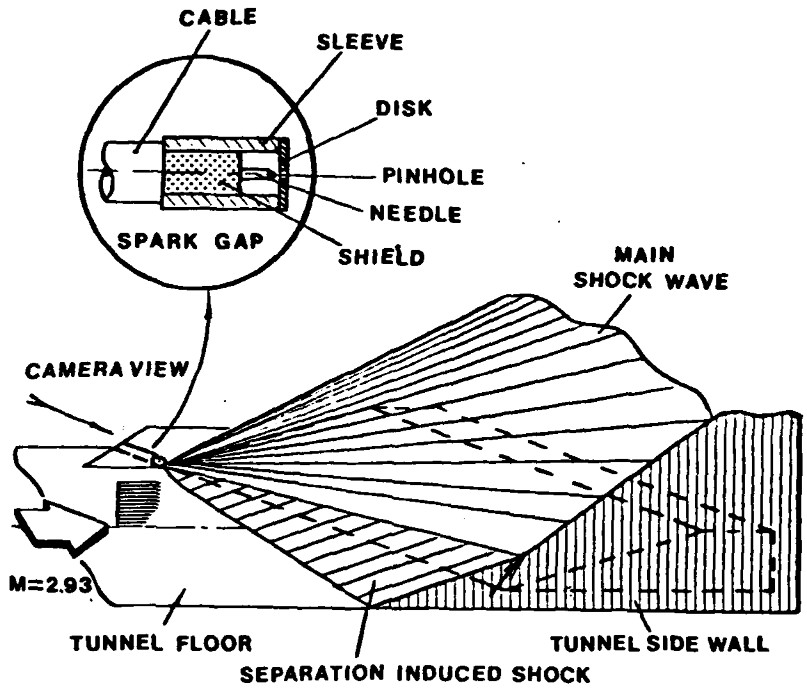


Fig. 11. Sketch of Swept Compression Corner Geometry.

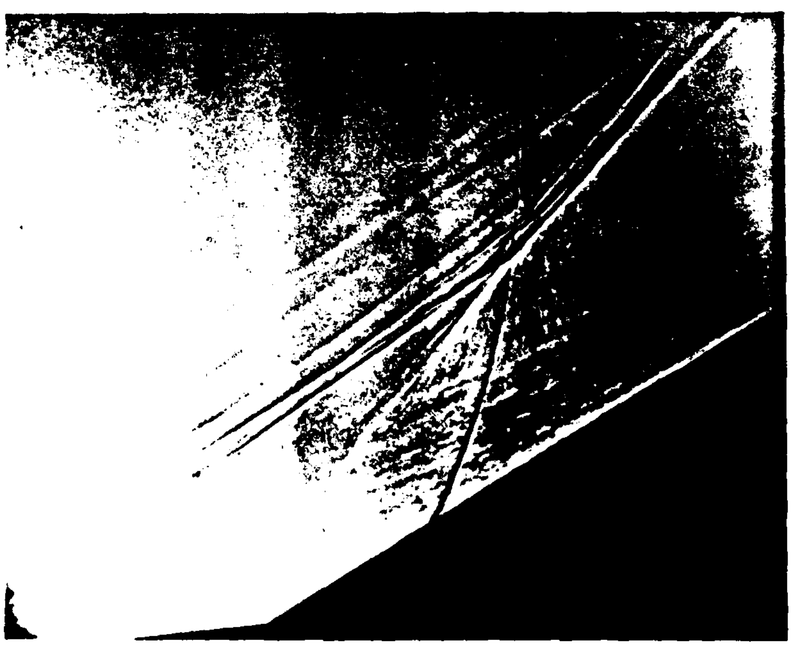
Fig. 12. Stereo Pair Showing Acetone Injection Upstream of Separation Zone (λ = 40°).

Fig. 13. a) Sketch of Conical Shadowgraph Arrangement for Swept Compression Corners.

b) Conical Shadowgram ($\lambda = 40°$).



a)



b)

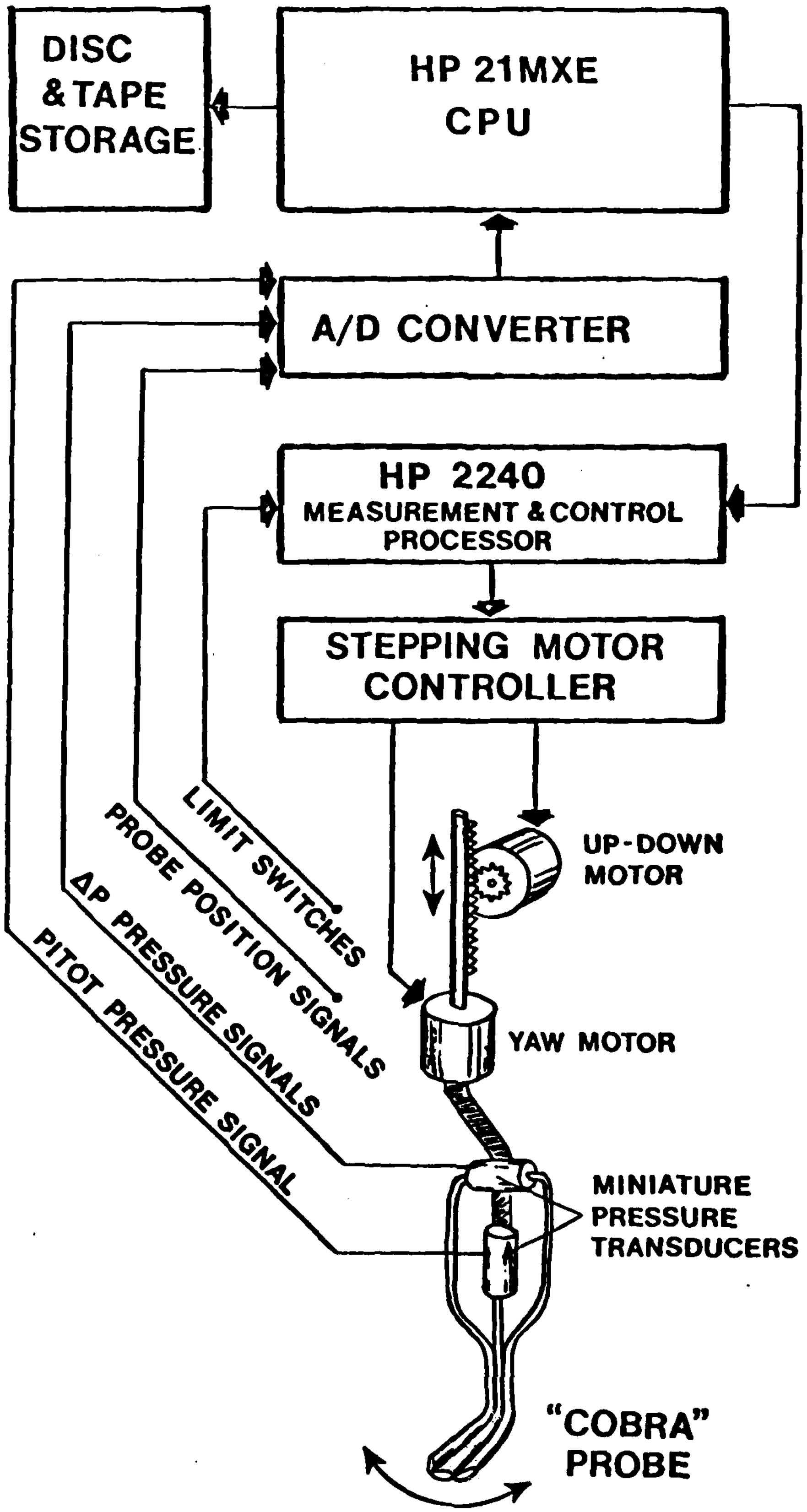


Fig. 14. Schematic of Computer-Driven Yaw Probe.